PULSED POWER HYDRODYNAMICS: A DISCIPLINE OFFERING HIGH PRECISION DATA FOR MOTIVATING AND VALIDATING PHYSICS MODELS

R.E. Reinovsky
Los Alamos National Laboratory, PO Box 1663, MS D420
Los Alamos, New Mexico, USA 87545

Abstract

The discipline of Pulsed Power Hydrodynamics is a new application of low-impedance, pulsed power technology, developed to study implosion hydrodynamics, instabilities, turbulence, and material properties in a highly precise, controllable environment at the extremes of pressure and material velocity. The discipline of pulsed power hydrodynamics arose in response to the need for economical, high-precision data to validate sophisticated numerical models used in current numerical simulations and to motivate the development of new models for future simulations. The international capability in pulsed power technology that has evolved over several decades in response to numerous other programmatic needs played a pivotal role in the development of the new discipline by enabling demonstrations of the techniques and production of introductory data long before a dedicated facility could be conceived, planned, and built.

The high-precision, cylindrically imploding liner is the tool most frequently used to convert electromagnetic energy into the hydrodynamic (particle kinetic) energy needed to drive strong shocks, quasi-isentropic compression, or large volume adiabatic compression for the experiments. At typical parameters, a 30-gr, 1-mm-thick liner with an initial radius of 5 cm, driven by a current of 20 MA, can be accelerated to 7.5 km/sec producing mega-bar shocks in medium density targets. Velocities up to 20 km/sec and pressures >20 Mbar in high density targets are possible.

The Atlas facility, designed and built by Los Alamos, houses the world's first laboratory pulsed power system designed specifically to explore this relatively new family of pulsed power applications. Constructed in the year 2000 and commissioned in August 2001, Atlas is a 24-MJ, high-performance capacitor bank delivering currents up to 30 Megamperes with a rise time of 5 to 6 μsec. The first Atlas liner implosion experiments were conducted in September 2001, and 16 experiments were conducted in the first year of operation before Atlas was disassembled to be moved to the Nevada Test Site, where experiments began again in July 2005.

Applications of pulsed power hydrodynamics techniques currently include material property topics such as: exploration of material strength at high rates of strain; material failure including fracture, damage, and spall; and interfacial dynamics at high relative velocities and high interfacial pressures. Implosion dynamics and a variety of complex hydrodynamic geometries have been explored and experiments to explore perturbation growth and transition to turbulence are under consideration. Longer term applications include the study of the behavior and properties of strongly coupled plasmas and the equation of state of metals and non-metals at pressures above 10 Mbar. This paper will provide an overview of the programmatic evolution that led to the birth of the discipline of pulsed power hydrodynamics.

I. INTRODUCTION

Pulsed Power Hydrodynamics (PPH) is among the newest applications of pulsed power to emerge from the steadily advancing development of electromagnetic capability and techniques that include increasing power and energy, but also improved reliability, reproducibility, and economy. The evolution of pulsed power hydrodynamics has been shaped by the need for high precision experimental data to validate sophisticated physics models used in modern computer simulations and to improve the physics in those models. The development of the discipline has been aided by the availability of a variety of working platforms, world-wide, in the form of both laboratory and field test systems developed over the last 50 years. And the discipline has, in less than a decade, made numerous contributions motivating the development of new physics models and validating existing ones in order to increase confidence in the results of the computer simulations that are increasingly replacing field testing in many disciplines.

II. DISCIPLINE OF PULSED POWER HYDRODYNAMICS: REQUIREMENTS AND CONTEXT

Programs that sponsor the development of the major pulsed power technologies and systems have traditionally, and appropriately, evolved in response to specific, but frequently varied, and relatively well-understood needs. As electric utility technology evolved, industrial

Report Documentation Page			*Form Approved* *OMB No. 0704-0188*
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.			
1. REPORT DATE **JUN 2005**	2. REPORT TYPE **N/A**		3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Pulsed Power Hydrodynamics: A Discipline Offering High Precision Data For Motivating And Validating Physics Models**			5a. CONTRACT NUMBER
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)			5d. PROJECT NUMBER
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Los Alamos National Laboratory, PO Box 1663, MS D420 Los Alamos, New Mexico, USA 87545**			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**			
13. SUPPLEMENTARY NOTES **See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.**			
14. ABSTRACT **The discipline of Pulsed Power Hydrodynamics is a new application of low-impedance, pulsed power technology, developed to study implosion hydrodynamics, instabilities, turbulence, and material properties in a highly precise, controllable environment at the extremes of pressure and material velocity. The discipline of pulsed power hydrodynamics arose in response to the need for economical, high-precision data to validate sophisticated numerical models used in current numerical simulations and to motivate the development of new models for future simulations. The international capability in pulsed power technology that has evolved over several decades in response to numerous other programmatic needs played a pivotal role in the development of the new discipline by enabling demonstrations of the techniques and production of introductory data long before a dedicated facility could be conceived, planned, and built.**			
15. SUBJECT TERMS			

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

requirements, particularly from the utility industry, identified needs for component testing and qualification capability that led to the establishment of pulsed power laboratories employing early Marx systems and other, more conventional, high-voltage systems including transformers for testing cables, insulators, and switch gear. The capability of pulsed magnetic fields to distort, form, and fuse metals led to a variety of industrial fabrication applications, and in recent years, to applications in food processing. Certainly among the seminal applications of pulsed power for advanced research applications, have been those of the fusion community where pulsed power is applied for confining and heating magnetic confinement plasmas; for driving intense lasers for inertial confinement applications; and as the core technology for the intermediate but less well-developed family of fusion application known as Magnetized Target Fusion (MTF). While fusion energy continues to be a major scientific grand challenge, production of intense neutron sources for research applications on the way to the realization of net energy from fusion, is also important.

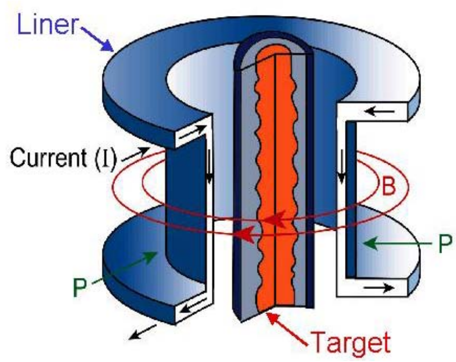

Figure. 1. Z-pinch Liner implosion geometry.

One of the other seminal research applications was in the area of nuclear weapons science and technology where high peak power systems were needed to power a variety of simulators for nuclear weapons effects such as the generation of x-ray, hydrodynamic (shock), and electromagnetic effects, as well as for powering a wide variety of physics experiments. Hot dense plasmas produced by the world's highest energy, highest power systems continue to be important for (x-ray) radiation production, enabling the study of the interaction of radiation with materials and the study of radiation transport. Electron beams, similarly powered by some of the highest power systems, continue to be used for x-ray production as both wide area sources for effects studies and concentrated into pinpoint spots for dynamic radiography, especially of fast moving, thick, high atomic number mechanical assemblies. A variety of pulsed power systems are used to power linear induction accelerators producing medium- and high-energy beams for fundamental investigations in nuclear and particle physics.

Joining these plasma and beam applications is the recently emerging use of low impedance, very high current pulsed power sources for direct hydrodynamic applications in material properties studies at pressures and temperatures otherwise inaccessible, and for the study of advance high energy density fluid dynamics, implosion dynamics, and fluid instabilities at extreme conditions. Add to these advanced non-nuclear defense applications such as directed energy; homeland defense through a variety of approaches to active interrogations, microwave and rf applications; electromagnetic projectile acceleration, and special operations applications and the opportunities for programs applying pulsed power expand significantly.

In that part of nuclear weapon science activities called Stockpile Stewardship, experimentally based development, test and evaluation in the form of underground nuclear testing has been replaced by numerical simulation-based system certification using the best computer hardware with best physics models available. The reliance on simulations to replace testing brings into focus questions of just how good are the models used to make important decisions, and the further question of how additional investments should be made to improve those models. Selected new experimental data are of continuing importance in increasing confidence in the accuracy and completeness of simulations based on these models. New experimental techniques expanding the parameter space in which high precision, reliable, and reproducible data is conveniently and economically available is essential for "validating" the physics models used in modern simulations. Pulsed power approaches to enabling such fundamental experiments play a crucial role now and in the future.

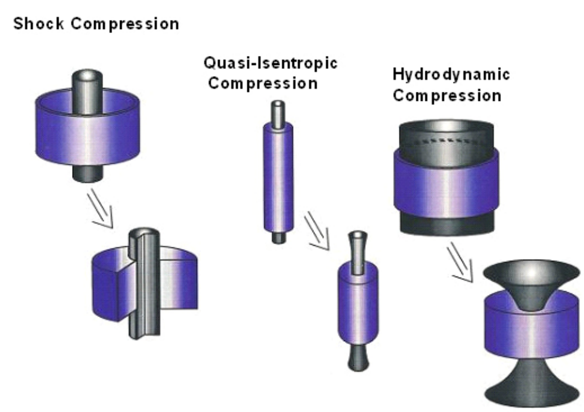

Figure 2. Magnetically imploded liners can be used to produce a variety of useful hydrodynamic environments.

The development of the discipline of pulsed power hydrodynamics, with its heritage deep in the concepts of repetitive hydrodynamic implosions (LINUS) and fast liner compression of fusion plasmas, was strongly influenced by the success in the early 1990's of fast plasma liner implosions at Sandia National Laboratories (Albuquerque) as intense x-ray sources. Through an evolving series of experiments on very fast (100-ns), ultra-high-power pulsed power machines, beginning on Proto II and continuing on Saturn, PBFA (Z), the Z Machine, and in the future to be continued on the Z-R machine, the efficacy of high velocity >>30-cm/μsec plasma liner implosions for x-ray production was demonstrated. Beginning in the early 1990's, the application, and later optimization, of longer pulse systems featuring very high currents delivered in microseconds for ultra-precision acceleration of condensed matter to more modest velocities (1–2 cm/μsec, 10–20 mm/μsec was begun using systems such as Shiva Star at the AFRL, and Pegasus and its successor Atlas, at Los Alamos. The requirements for such high precision experiments emerged first in relation to exploring material properties, both equations of state and constitutive properties at extreme conditions, and advanced implosion hydrodynamics and instabilities studies. This effort developed into the discipline called pulsed power hydrodynamics.

Pulsed power hydrodynamics uses magnetically driven, ultra-high-precision implosions to conduct hydrodynamics experiments in condensed matter. These experiments are designed to motivate the development of new models of material behavior at extreme conditions and to validate existing models in regimes beyond those accessible through existing techniques. The conventional z-pinch implosion (Fig. 1) is the most frequently used geometry. In this geometry, 10 to 100-gram aluminum liners are smoothly and uniformly imploded by the magnetic field produced by 10's of MA of current delivered from an ultra-low impedance, microsecond pulsed power source. The imploding liner, with its several megajoules of kinetic energy, can be applied in several applications (Fig. 2) including direct impact on a target to produce intense shock pressure of 100's of kbar in light materials and several Mbar in high density materials. The liner can similarly be used to apply the magnetic pressure directly to a sample to achieve quasi-isentropic compression of the sample without shocks—and without the complication of magnetic fields penetrating to the sample. Similarly, the liner can perform significant PdV work on a fluid, converting liner kinetic energy into internal energy in the compressed gas, plasma, or magnetized plasma, heating and compressing the fluid in times relatively short compared to energy loss times.

While some of the advantages of the high precision cylindrical implosion geometry can be achieved in other ways (such as by cylindrical implosions directly driven by high explosives), magnetically driven implosions offer a number of unique advantages:

- Magnetic fields are transparent to visible light and to x-rays, making the evaluation of target behavior with imaging diagnostics much easier by eliminating the attenuating and contrast-reducing effects of the HE products.
- Magnetic fields are fundamentally cylindrical, exactly matching the basic geometry of the experiment and complementing the planar capability of high performance gas guns. Uniform, cylindrical implosion geometries deliver the multi-dimensional effects of converging systems coupled with both axial and transverse (radial) diagnostic access.
- Magnetic field drive is "dialable," controllable, and reproducible. The setting of one knob permits adjustment of drive energy and hence implosion velocity and energy. A factor of 5 change in operating parameters results in a factor of 25 change in operating pressure. Significantly, better than 1% control and reproducibility has been demonstrated.
- Magnetic field drive is immediately adaptable to large (cm-scale) targets complementing, though at lower velocity, the very high energy density drive available from high energy lasers on mm and sub-mm size targets.
- Magnetic fields can provide high explosive-like shock pressures without shocks, thereby providing access to off-Hugoniot states of matter complementing traditional HE driven equation-of-state techniques.
- Magnetic fields deliver energy at the speed of light without accompanying mass, providing fundamentally faster velocities than can be achieved with HE or gas guns where the sound speed in the driving fluid sets the upper limit of energy delivery to the working package. Energy delivered masslessly gives rise to much less collateral impulse imposed on the surroundings, making confinement and, if necessary, complete containment, of experimental materials easier.
- Magnetic fields can be removed almost instantly, by switching systems, allowing delivery of only the required amount of energy—and no more—enhancing sample recovery for post-shot analysis
- Energy for magnetic drive can fundamentally be stored (e.g., in capacitors) that are remote from the experiments enhancing overall safety of operations involving hazardous materials.

III. WORLD-WIDE CAPABILITIES MADE POSSIBLE THE DEVELOPMENT OF A NEW DISCIPLINE

The pulsed power community, world-wide, has developed an impressive ensemble of capabilities (facilities and fieldable systems) that support pulsed power hydrodynamics activities and that have made possible the development of the new discipline. The development of many of these capabilities preceded the formal establishment of a program by that name.

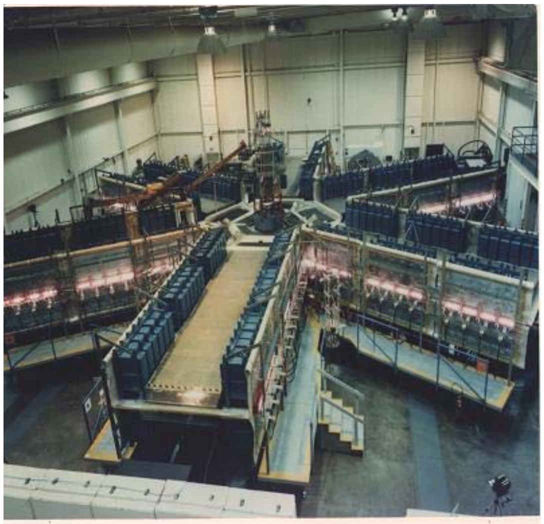

Figure 3. The Shiva Star 9-MJ liner driver at the Air Force Research Laboratory.

First commissioned in 1976 by the Air Force, the Shiva family of >10-MA, microsecond rise time, pulsed power systems developed at the Air Force Research Laboratory have a long history of performing both plasma and pulsed power hydrodynamics experiments. Initially built to drive microsecond plasma liner implosions for x-ray source production, [1] the fourth in the family of systems, Shiva Star, (Fig. 3) has been used to perform a variety of experiments addressing the physics and performance of high precision liners. In 2000, Shiva Star performed a series of "Near Term Liner Experiments" [2], extending contemporary liner implosion research to 15-MA drive conditions while demonstrating excellent stability of the back surface, liner/field interface: a result that was later to be in surprising contrast to that obtained on the Atlas facility at Los Alamos at only slightly higher current and slightly shorter pulse duration. In the NTLX series, Shiva Star also produced unique data on complex hydrodynamic situations tracking shocks through symmetric and asymmetric geometries to validate the hydrodynamics in evolving computer simulations [3]. For magnetized target fusion (MTF) applications, a long (30-cm) uniform, high-precision liner implosion is needed. Unique experiments demonstrating successful operation of such long liners have been conducted on Shiva Star marking one important milestone in the development of MTF capability [4]. MTF experiments have the further complexity of requiring imploding liners that operate free from the introduction of extraneous material into the plasma. Recently, experiments extending liner performance by introducing the deformable liner contact and its corollary, shaped and mass contoured liner implosions have been demonstrated on Shiva Star to provide quasi-spherical compression geometries [5].

Experiments on the Los Alamos Pegasus system (Fig. 4), conducted from 1994–1998, explored the details of high precision liner implosions for their application to hydrodynamics, instabilities, and dynamic material properties experiments at extreme conditions. Like other facilities at the time, Pegasus was initially developed to perform microsecond duration plasma liner implosions [6]. But in 1994, the development program on Pegasus was redirected to explore solid liner implosions, conducting the first of the contemporary family of experiments that demonstrated the potential for clean, high-precision, and reproducible liner implosions—experiments that ultimately led to the application called pulsed power hydrodynamics. From 1994, until its decommissioning (in favor of Atlas) in 1999, Pegasus conducted almost 100 applied and exploratory experiments in more than eight topical areas [7]. Pegasus experiments demonstrated high-resolution diagnostics of perturbation growth (instabilities) at both hydrodynamic and magneto-hydrodynamic interfaces (interior and exterior surfaces) of magnetically driven liners and explored some of the details of shell-on-shell collisions [8].

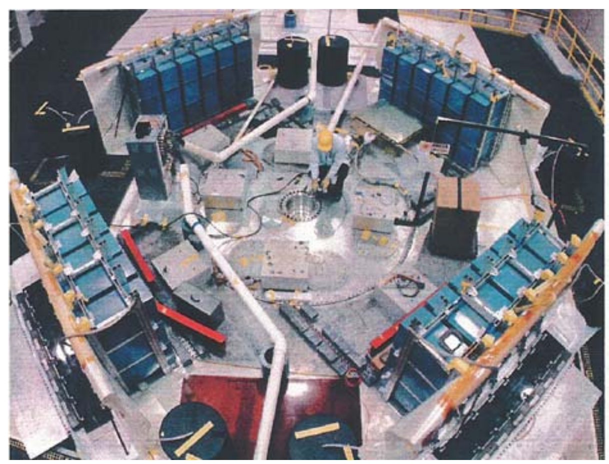

Figure 4. The Pegasus 10-MA driver at Los Alamos.

Other Pegasus experiments produced similarly high-quality imaging data of the hydrodynamic evolution of small defects such as gaps, or offsets in otherwise uniform and symmetric cylindrical hydrodynamic implosions. Yet, other Pegasus experiments explored the strength of metals at high rates of strain (HSR) by measuring energy dissipation (through temperature rise) in thin shell implosions, and the evolution of debris (EJECTA) from a shocked free surface. Both the instability and advanced hydrodynamics experiments validated some aspects and challenged other aspects of the most sophisticated hydrodynamics models of the day. The HSR and EJECTA experiments similarly challenged contemporary models of constitutive properties of common reference materials. Diagnostics developed for dynamic liner experiments on Pegasus: high resolution, medium energy radiography, laser shadowgraphy and holography for tracing particulates, VISAR for pulsed power applications later played significant roles in other aspects of the nuclear weapons physics programs at other facilities.

In 1994, Los Alamos began a programmatic effort to design and build a major facility, Atlas, initially for both plasma and condensed matter implosion experiments. By 1996, development of high speed wire array implosion on the Z-Machine at Sandia National Laboratories was providing high performance x-ray sources. The Sandia success focused the Atlas design on condensed matter liner implosions (and pulsed power hydrodynamics). During the 7-year process of designing and building Atlas, PPH experiments were conducted at a number of venues to both explore and validate the concept of condensed matter implosions as tools useful for high-precision physics applications.

Figure 5. Disk Explosive Magnetic Generator system at VNIIEF used to conduct HEL-1 liner compression experiment.

One such venue was the All Russian Scientific Research Institute of Experimental Physics (VNIIEF), Sarov, Russia where Andrey Sakharov pioneered the forerunner of pulsed power hydrodynamics in Russia beginning in the mid-1950's, primarily for fusion plasma compression. Sakharov's work led to the development of a family of (single-use) explosively driven pulsed power systems—work that was carried on by teams led by the late Vladimir Chernyshev, Alexander Pavlovskii, and Robert Ludaev in the form of helical, coaxial, and disk configuration explosive magnetic pulsed power generators. In 1996, while Atlas was still in preliminary design, Los Alamos and VNIIEF teamed to conduct a high energy liner, called HEL-1 (Fig. 5). The HEL-1 experiment used one of the most powerful Russian pulsed power systems, the 1-m-diameter Disk Explosive Magnetic Generator (DEMG), to implode a 1-kg, 40-cm-diameter aluminum liner to 7–8 km/sec (22–25 MJ of kinetic energy) using 100-MA current pulse [9]. The HEL-1 experiment was aimed at demonstrating the upper end of PPH capability (as of the mid-1990's) and at the same time challenging current simulation tools to correctly model the implosion behavior. Both Russian and US simulation techniques were applied to model the experiment with the result that, while neither set of tools provided complete descriptions of implosion behavior, both added significant insights—and confirmed the basic validity of the modeling technique.

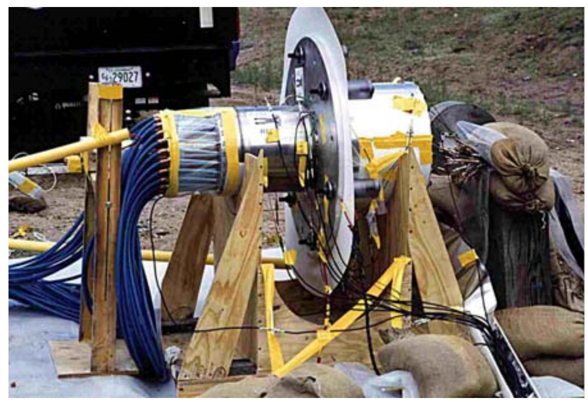

Figure 6. Ranchero coaxial flux compressor powering Atlas prototype liner implosions.

During the same period, development of explosive pulsed power systems in the US for PPH applications was focused, not on further extending the limits of condensed matter liner performance, but rather, addressing Atlas-specific problems in implosion dynamics and stability and technological problems of power transport. The Ranchero, simultaneous, coaxial flux compression generator (Fig. 6) was developed and provided, in 1998, near Atlas-like, 15–30 MA, current wave forms [10]. Ranchero experiments provided the first test of Atlas scale liner implosions at about 15 MA, along with demonstrations of power flow in solid insulated transmission lines and through solid vacuum interfaces that guided future designs for Atlas power-flow systems. These experiments were notable for their successful simultaneous application of sophisticated imaging (x-radiography) and continuous surface position and velocity measurements (VISAR) at >10-MA currents and in the explosive environment.

In November 2000 through May 2001, as Atlas neared completion, another series of developmental experiments for pulsed power hydrodynamics techniques were conducted at VNIIEF called the Advance Liner Technology (ALT) experiments (Fig. 7). For the ALT-series, the VNIIEF team designed a pulsed power system consisting of a DEMG power source and active switching for pulse forming [11].

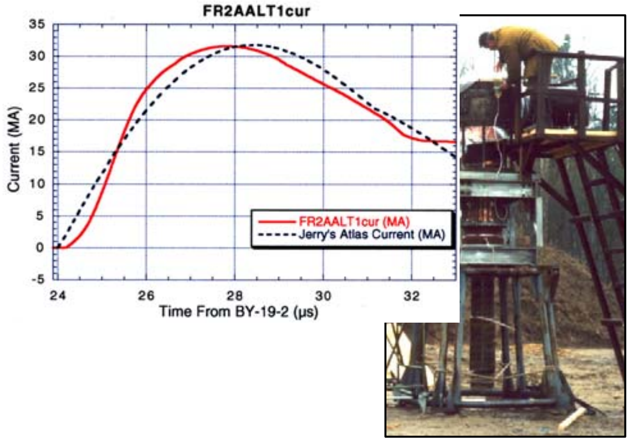

Figure 7. ALT experiments at VNIIEF demonstrated full (Atlas) scale performance, 30-MA liner implosions.

In operation, the ALT system produced a 30-MA waveform that nearly matched the (then-predicted) Atlas waveforem. Simultaneously, the LANL team was finalizing the parameters for the first Atlas liner experiments—and those parameters were directly tested in the ALT experiments. VISAR measurements tracked the velocity of the inner surface of the liner to >12 km/sec, in good agreement with 1D MHD calculations, demonstrating performance more than adequate for the initial series of material properties (friction, spall, and strength) planned for the Atlas system. Initial attempts at radiographic imaging were unsuccessful because of damage to the recording film, leaving unanswered the question of liner stability at current above 15 MA in Atlas configurations.

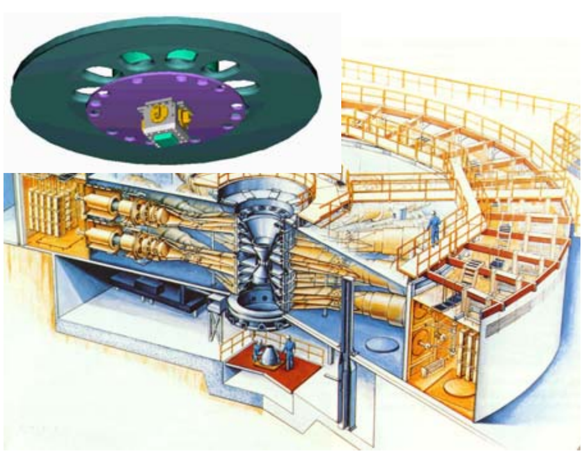

Figure 8. Sandia developed off-Hugoniot techniques using the Z-machine.

In the late 1990's, Sandia pioneered an approach for exploring the response of metals in conditions away from the principal Hugoniot (locus of points reachable by one shock in a specific material)[12]. The Sandia approach capitalizes on the fact that magnetic drive can apply a continuous (non-shock, ie. ramp) pressure loading to a sample; and that the pressure history is precisely known from measurements of the current and of the simple geometry as it takes the target material through a series of non-shock, or off-Hugoniot states. Evaluating the response (stress) of the target material to the known drive, as a function of time, by comparing the particle velocity measured after the pressure wave is transmitted through different thicknesses of sample allows the interrogation of the whole family of states in a single experiment. Sandia applied the technique to metals for pressures up to 1 Mbar in experiments on Saturn and the Z machine (Fig. 8). The Z-R machine will allow extension of the technique to even higher pressure conditions. At the same time, LANL was exploring similar techniques using the higher currents and hence ultimately higher pressures potentially available from explosive pulsed power systems as well.

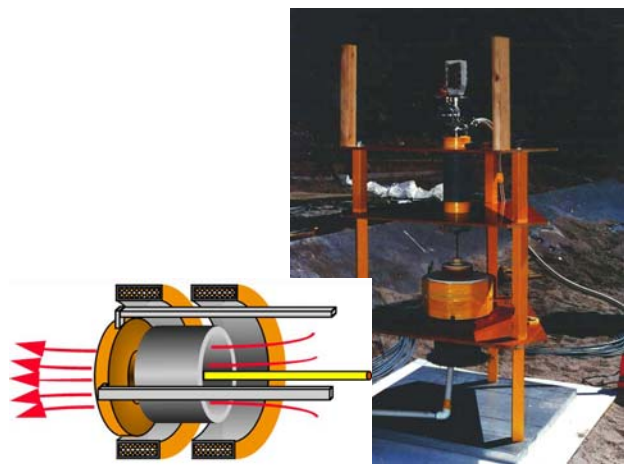

Figure 9. The MC-1 high magnetic field generator provides 1000-T fields using hydrodynamically and magnetically driven liners. Liner compressed fields can be explored on laboratory capacitor banks—large and small.

Pulsed power hydrodynamics enables yet another capability through the use of high velocity liners to drive magnetic flux compression experiments that can potentially produce multi-Megagauss magnetic fields in volumes sufficiently large to conduct solid state physics experiments. Two techniques have been considered (Fig. 9). The VNIIEF-designed and built MC-1 high magnetic field generator uses a combination of hydrodynamic (HE-driven) and magnetically driven, multi–stage liners to produce >1000 Tesla. The MC-1 generator has been used extensively in Russia, and exported to other countries (US) [13], where they have been used to explore the physics of materials at very high magnetic fields. Similarly, magnetically imploded single- or multi-stage liners have been demonstrated on small laboratory capacitor systems in Japan [14] and Europe [15], producing fields around 1 MG. Using Atlas and other large laboratory generators to compress magnetic flux without high explosive, computationally permits access to fields of several MG and perhaps as high as 10 MG (1000 T). Such high fields open a whole new family of research applications including: the measurement of the critical field for high temperature superconductors; exploration of the Fermi surface topology with de Haas-van Alphen effect; behavior of atomic electrons at low principal quantum numbers; optical properties of materials at high fields; and quantum limit phenomena in anisotropic metals.

Figure 10. Atlas facility at Los Alamos.

Among all the capabilities world-wide that have significantly advanced the discipline of pulsed power hydrodynamics, Atlas is the first, and only, pulsed power system specifically optimized for driving PPH experiments (Fig. 10) [16]. It is the world's newest, ultra-low impedance, high-current capacitor bank facility, specifically designed for executing solid-density liner implosions, and is the flagship facility for PPH experiments at this time.

Conceptual development for Atlas began in 1992. Component selection, development, and testing continued through 1996, when the final configuration was selected and engineering design begun. Construction began in late 1999 and assembly was completed in August 2000. Atlas passed its pulsed power acceptance tests in December 2000 and achieved operational status after a series of pulsed power characterization tests in August 2001. Atlas was operated at Los Alamos until late 2002 [17]. It was then disassembled and reassembled at the Department of Energy's Nevada Test Site (NTS) where it was re-commissioned in July 2005. Pulsed power hydrodynamics experiments began on Atlas in the same month, and continued through June 2006 [18].

Pulsed Power Hydrodynamics experiments conducted in the field or laboratory are diagnosed with techniques that must be fielded in the sometimes challenging environment produced by the driver system. Sometimes it is the capability of the currently available diagnostics that sets the limit on the usefulness of the experiment, and not the drive technology. Some diagnostic techniques, proton radiography, for example, have significant advantages, such as enhanced resolution and multi-frame imaging on precisely the same line-of-sight, but simply cannot be fielded at existing drivers. To access those advantages, a pulsed power driver suitable for the diagnostic environment must be developed. The Precision High Energy Liner Implosion Experiment (PHELIX) is one example of such a driver currently under consideration (Fig. 11). Since space is a fundamental limitation in the proton beam environment, the PHELIX driver must provide sufficient energy to drive smaller scale liner implosion experiments. Since the higher resolution of the Prad diagnostic allows the size of the experiments to be reduced, lower total energy is required from the driver. A unique feature of the PHELIX concept is the use of a closely coupled, fast transformer immediately surrounding the liner, which, ultimately, delivers current to drive the liner.

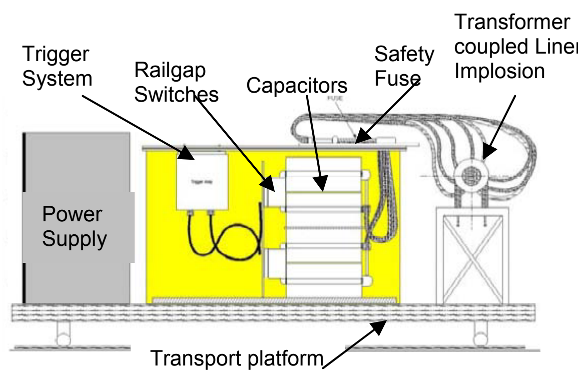

Figure 11. The PHELIX system allows pulsed power hydrodynamic experiments to be conducted using diagnostics that cannot be moved to an existing PPH machine.

IV. SUMMARY

The discipline of Pulsed Power Hydrodynamics arose in response to the need for economical, high-precision data to validate the sophisticated numerical models used in current numerical simulations and to motivate the development of new models for future simulations. The international capability in pulsed power technology that has evolved over several decades, in response to numerous other programmatic needs, played a pivotal role in the development of the new discipline by enabling demonstrations of the techniques and production of introductory data long before a dedicated facility could be conceived, planned, and built. New disciplines sometimes stimulate the development of new, dedicated facilities that advance the work of the discipline, and new technological facilities frequently outlive the program for which they were created and go on to enable new and even more creative endeavors.

V. REFERENCES

[1] W.L. Baker et al, “Electromagnetic – implosion generation of pulsed high-energy-density plasma, JAP 49, No. 9, 1978, p. 4695.

[2] P.J. Turchi et al, “Design, fabrication, and operation of a high energy liner implosion experiment at 16 MA, IEEE Trans. Plasma Physics 30, No. 5, 2002, p. 1777.

[3] R. Kanzleiter et al, “Using pulsed power for hydrodynamic code validation,” in Proc. of the 13th IEEE Internat. Pulsed Power Conf., LV, NV, 2001, p 1410.

[4] J.H. Degnan et al, “Research on magnetic pressure implosions of long cylindrical liners suitable for subsequent compression of the FRC type of compact toroids”, in Proc. of the 9th Internat. Conf. on Megagauss Magnetic Field Generation and Related Topics, Moscow-St Petersburg, 2002, p. 730.

[5] J.H. Degnan et al, “Full axial coverage radiography of deformable contact liner implosion performed using 8-cm-diameter electrode apertures, in Proc. of the 15th IEEE Internat. Pulsed Power Conf., Monterey, CA, 2005.

[6] H. Oona et al, “Experimental studies of instabilities in radially imploding plasmas,” Proc. of the 6th Internat. Conf. on Megagauss Magnetic Field Generation and Related Topics, Albuq., NM, 1991. p. 899.

[7] R.E. Reinovsky and R.J. Trainor, “Hydrodynamics and material properties experiments using pulsed power techniques," in Shock Compression of Condensed Matter-1999, Am. Inst. of Physics Proceedings, p. 505.

[8] R.E. Reinovsky et al, “Instability growth in magnetically imploded high conductivity, cylindrical liners with material strength,” IEEE Trans. Plasma Physics 30, No. 5, 2002, p. 1777.

[9] R.J. Faehl, “Results of a 100-MA liner implosion experiment,” IEEE Trans. Plasma Physics 32, No. 5, 2004, p. 1972.

[10] J.H. Goforth et al, “Ranchero explosive pulsed power experiments” and “Modeling and analysis of the Rancheo coaxial explosive pulsed power generator system,” Proc. of the 12th IEEE Internat. Pulsed Power Conf., Monterey, CA, 1999, p. 329.

[11] A.M. Buyko et al, “Simulation of Atlas parameters in explosive magnetic experiments ALT 1-2,” in Proc. of the 9th Internat. Conf. on Megagauss Magnetic Field Generation and Related Topics, Moscow-St Petersburg, 2002, p. 747.

[12] J.R. Asay, “Isentropic compression experiments on the Z accelerator,” in Shock Compression of Condensed Matter- 1999, Am. Inst. of Physics Proceedings, No.505.

[13] R.G. Clark et al, "The Dirac experiments—results and challenges," in Proc. of the VIIIth Internat. Conf. on Megagauss Magnetic Field Generation and Related Topics, 1998, p. 12.

[14] N. Miura et al, "Generation of megagauss fields by electromagnetic flux compression and the single-turn technique at ISSP," in Proc. of the VIIIth Internat. Conf. on Megagauss Magnetic Field Generation and Related Topics, 1998, p. 663.

[15] M. von Ortenberg and H.U. Mueller, "Nondestructive mini-coils approaching megagauss fields," in Proc. of the VIIIth Internat. Conf. on Megagauss Magnetic Field Generation and Related Topics, 1998, pg. 171.

[16] R.E. Reinovsky et al, “Pulsed power hydrodynamics: a new application of high magnetic fields,” 9th Internat. Conf. on Megagauss Magnetic Field Generation and Related Topics, Moscow-St Petersburg, 2002, p. 696.

[17] R.E. Reinovsky et al, “Atlas performance and imploding liner parameter space,” 9th Internat. Conf. on Megagauss Magnetic Field Generation and Related Topics, Moscow-St Petersburg, 2002, p. 399.

18] R.E. Reinovsky et al, “Applying magnetically imploded liners to study hydrodynamics, instabilities, and material properties,” presented at the VII Khariton Scientific Readings, Sarov Russia, March 2006.